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LIGHT-EMITTING DIODES FOR LASER PUMPING

Harvey V. Winston

Hughes Aircraft Company

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by

HARVEY V. WINSTON

JULY 1972

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This report reviews the published literature on the application of light-emitting diodes to the pumping of solid-state laser rods. Because of the requirements of matching the LED output to the absorption bands of the active laser impurity ions, most work in this field has concentrated on the ternary alloy LED's such as gallium aluminum arsenide and gallium arsenic phosphide systems. Data tables on these materials are appended to the report.

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LIGHT-EMITTING DIODES FOR LASER PUMPING

SUMMARY

This report reviews the published literature on the application of light-emitting diodes to the pumping of solid-state laser rods. Because of the requirement of matching the LED output to the absorption bands of the active laser impurity ions, most work in this field has concentrated on the ternary alloy LEDs such as $GaAs_{1-x}P_x$ and $Ga_{1-x}Al_xAs$, which can be tuned by [illegible]ng their composition. These alloy systems have been actively developed in connection with visible display applications, and the laser pumping application has benefited from advances in this technology. Successful operation of $YAG:Nd^{3+}$ lasers pumped by $GaAs_{1-x}P_x$ diode arrays has been achieved; $YAG:Nd^{3+}$ has absorption bands near 8100 Å which correspond to efficient emission wavelengths in both ternary alloys mentioned. For this reason, the $YAG:Nd^{3+}$ appears to be the best choice for the laser to be pumped as well as for its 1.06 micron output, which is compatible with good detectors and thus suitable for many communications and ranging systems. The key to efficient operation of a diode-pumped laser is the optical and thermal design of the pumping cavity combined with a laser resonator design which optimizes the utilization of pumping light. Diodes of both alloys must be operated at junction current densities greater than 1000 A/cm^2 to provide enough output power for laser pumping, and it is not known what operating lifetime can be expected. Future work on LEDs for laser pumping will probably be concentrated on achieving long operating lifetimes while maintaining the high efficiencies which are already available.

Appended to the report are data tables on the gallium aluminum arsenide and gallium arsenide-phosphide systems complete with individual bibliographies.

LIGHT-EMITTING DIODES FOR LASER PUMPING

Since the early days of solid-state lasers and p-n junction electroluminescent diodes, workers in both fields have been striving to combine the two technologies to produce efficient diode-pumped solid-state lasers. Efficient operation was expected to result from matching the narrow absorption bands of the active laser impurity ions in solid-state laser hosts. The first published work suggesting the feasibility of this approach was by Newman. Although he did not actually demonstrate laser action, he was able to excite the 1.06 μm fluorescence of Nd^{3+} in a $CaWO_4$ host by means of light emitted from selected GaAs p-n junctions. He showed that some GaAs junctions, made by particular fabrication techniques, emitted in the 8650-8900 Å absorption band of $CaWO_4$: Nd^{3+}, while emission from other junctions fell outside this band.

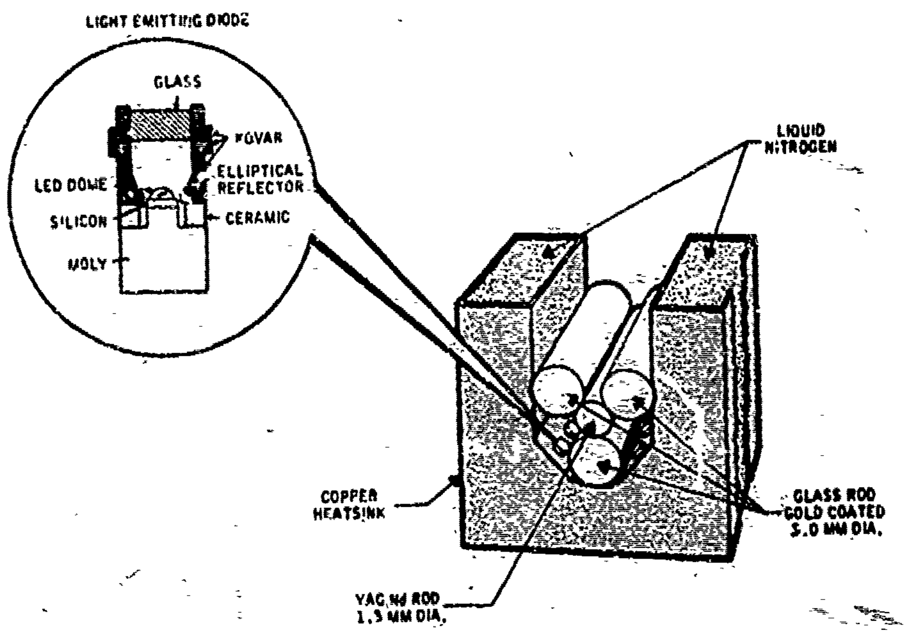
The first actual laser operation with LED (light-emitting diode) pumping was achieved by Ochs and Pankove. They employed a CaF_2:Dy^{2+} laser rod, with laser emission at 2.36 μm, pumped in its 7200 Å absorption band by a $GaAs_{0.73}P_{0.27}$ LED at 77°K. The laser rod operated at pumped-helium temperature, and was limited to 0.2 seconds of operation by internal heating. This work introduced the idea of adjusting the composition (and thus the bandgap) of ternary III-V LEDs to match the pumping band of the solid-state laser. About the same time, Keyes and Quist used the emission of a GaAs diode laser at 8400 Å to excite a CaF_2:U^{3+} laser line at 2.631 μm. They also suggested the possibility of using a ternary, specifically $Ga_xIn_{1-x}As$, to produce pump radiation around 8750 Å for exciting Nd^{3+} lasers.

In these early attempts, the principles of diode pumping of lasers were clearly demonstrated, but practical problems also became evident. The solid-state lasers emitting in the 2-3 μm range were not desirable for many systems applications because of the lack of fast high-gain detectors. The Nd^{3+} emission at 1.06 μm is more desirable from this viewpoint, and the technology of YAG (yttrium aluminum garnet) as a Nd^{3+} host was developing rapidly. Harada and Suzuki described methods for making GaAs laser diodes emitting around 8700 Å and suitable for pulsed pumping of Nd^{3+}. Kruzhilin and Antonov also studied GaAs diodes for pulsed laser pumping, pointing out difficulties caused by internal heating in the diodes, including frequency shifts and changes in internal absorption. In 1968, Ross reported successful operation of a YAG:Nd^{3+}

pulsed laser, pumped at 200 pulses per second by a GaAs diode laser. The GaAs output was tuned to the absorption band of Nd^{3+} at 8675 Å by cooling the diode to 170°K. It was found that the YAG rod reached threshold with 0.06 millijoules of diode laser light, while 1.2 millijoules of flashlamp light were required. This demonstrates the efficiency advantage of narrow-band diode output as compared to broad-band flashlamp light, an advantage further accentuated by the decreased heating of the laser rod. In the context of using laser diode emission to produce pulsed YAG:Nd^{3+} operation, Ross emphasized that many pulses from many laser diodes could be collected by the YAG rod and emitted as a giant pulse with a small beam divergence and spectral width.

A joint effort by Texas Instruments (TI) and Bell Telephone Laboratories (BTL) investigators has demonstrated actual continuous room temperature operation of a $GaAs_{1-x}P_x$ diode-pumped YAG:Nd^{3+} laser. Their work confirms the feasibility of the concept but also spotlights the difficulties. We will review their results with particular emphasis on the LED characteristics they found necessary for laser pumping.

FIGURE I. LED PUMPED YAlG:Nd LASER. (Allen and Scalise).



In the first of a series of papers describing this work, Allen and Scalise of TI reported a system in which the $GaAs_{1-x}P_x$ LEDs were operated near 77°K. Figure 1 provides a schematic diagram of their diode-pumped YAlG:Nd laser. They employed $GaAs_{0.87}P_{0.13}$, which has an emission peak of 8025 Å at the operating temperature, and a linewidth between half-intensity points of 190 Å. This corresponds to the most intense absorption lines of $YAG:Nd^{3+}$, occurring near 8100 Å. They noted that a 1% increase in phosphorus content produces a 50 Å shift toward shorter wavelength and a 1°K decrease in temperature shifts the peak 2-3 Å toward shorter wavelengths. Their system contained 15 diodes mounted on a liquid-nitrogen-cooled copper heat sink; each diode was fabricated into a hemispherical dome 0.018-in. in diameter to reduce total internal reflection, and each diode package included a gold-plated elliptical reflector. The diodes could emit 50 mW at a power efficiency of 10%. (Junction diameter was not specified in this paper; in the later related papers it was given as 0.005 in.)

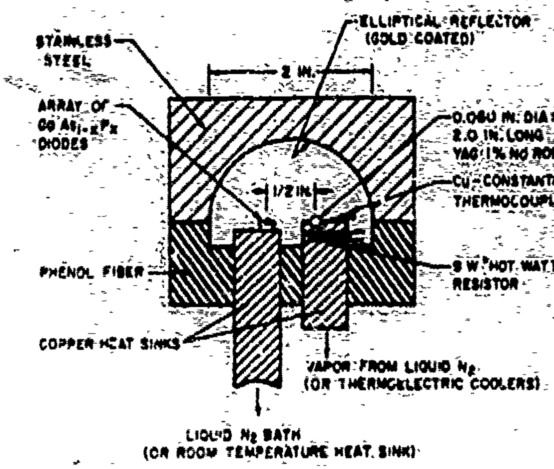
The laser output depends on the $YAG:Nd^{3+}$ rod, the laser cavity parameters, the optical coupling between the LEDs and the rod, and the temperature of the rod. Without attempting to optimize these, Allen and Scalise obtained 40 mW output at 1.064 μm with 8W of electrical power into the LEDs, for an overall efficiency of 0.5%. There is no direct provision for cooling the laser rod in their arrangement; its temperature drops slowly toward 77°K after the heat sink for the LEDs has been cooled. At first, the rod emits at 1.0641 μm, and then another transition at 1.0614 μm starts building. After 30 minutes, only the 1.0614 μm transition survives, with no further changes. It is known that the longer wavelength is characteristic for operation near 300°K, and the shorter wavelength for operation near 77°K. The 0.5% efficiency figure is for a laser rod 1.5 x 30 mm with deposited confocal end mirrors of 99.9 and 99.6% reflectivity. The lowest threshold observed was 300 mW electrical input to the diode array, using a 1 x 30 mm rod with the same mirror reflectivities operating at 1.0614 μm.

The next step toward room temperature operation was described by Ostermayer of BTL. He used $GaAs_{1-x}P_x$ diodes supplied by TI and apparently of the same design as those of Allen and Scalise. A major difference from the earlier TI study was the improved design of the pumping cavity, in which a linear array of LEDs was positioned at one focus of a semielliptic cylindrical reflector, with the $YAG:Nd^{3+}$ rod at the other focus. This provided nearly theoretically maximum

optical coupling between the pump diodes and the laser rod; also the laser rod had a reflecting channel or reflecting coating covering half its surface which allowed a double pass of pumping radiation. Finall, , the geometry allowed separate cooling and temperature monitoring for the diode array and the laser rod.

Ostermayer performed one experiment with LEDs operating at 77°K to determine the increase of the threshold power for YAG:Nd^{3+} with increasing laser rod temperature, achieving satisfactory agreement with a theoretical expression. The power efficiency of the 77°K diodes was 10-15%. Then, using the same laser rod and pumping cavity, Ostermayer installed a set of nineteen LEDs of the correct composition to emit 8100 Å at room temperature. These were mounted on a large copper heat sink and the whole assembly could be located precisely along the focal line of the semielliptic reflector with the help of an XYZ micropositioner and a rotating-tilting table. Figure 2 illustrates the apparatus used to perform the diode pumping experiments

FIGURE 2. APPARATUS FOR CONDUCTING DIODE PUMPING EXPERIMENTS. (Ostermayer)



A similar arrangement positioned the laser rod, which was attached to a heat sink cooled by thermoelectric coolers. With the LEDs operating at 250 mA/diode, (the maximum tolerable drive current, above which diode performance was somewhat degraded), Ostermayer determined the maximum laser rod temperature at which

threshold could be reached. With a 0.4% transmitting mirror on the laser rod the maximum temperature for threshold was -2.5°C; with both laser reflectors having high reflectivity, threshold was at 3.5°C. The room temperature LEDs were 4% efficient.

With a maximum drive current limitation on the output of each LED, a further increase in pumping power required more diodes in the linear array. Nineteen was the maximum number allowed in the 5 cm length of the pumping cavity by the dimensions of the individual LED packages in this work, but smaller packages would allow 60 or 80 diodes in the same space. Ostermayer predicted that with this arrangement it should be possible to obtain 50 mW continuously at room temperature from an LED-pumped YAG:Nd^{3+} laser.

The most recent report by Ostermayer, et al demonstrated room-temperature cw (continuous wave) operation, but only at 1.4 mW output. The paper includes a careful analysis of the effects which limit the laser output and suggestions for possible improvements. In this work, the advance which allowed room temperature operation was the increase in number of diodes in the 5 cm-long pumping cavity from 19 to 64. The individual diode elements were hemispherical domes of $GaAs_{0.85}P_{0.15}$, which emits near 8040 Å. The domes were 0.46 mm in diameter, with junctions 0.13 mm in diameter, on 0.71-mm square electrically insulating silicon submounts. The individual elements were mounted in a linear array on a common heat sink maintained at 20°C by flowing water through it.

The peak emission wavelength and the spectral bandwidth of the array, which determine the degree of spectral matching with the YAG:Nd^{3+} pump bands, vary with diode current because of heating effects. By comparing cw laser output powers with output powers after current pulses of a few milliseconds, and by correlating changes in laser output with changes in diode emission, the authors concluded that three effects combine to give a net decrease in pumping efficiency with heating of the diode array. A shift in peak wavelength from 7920 Å at low currents to 8020 Å at 225 mA/diode improves the efficiency, but is approximately compensated by a decrease in total power output with heating. The third effect is an increase in spectral bandwidth of the array, caused by differential shifts in the peak wavelength of different diodes according to the effectiveness of their heat sinking. The bandwidth increase causes some of the LED output to fall outside the absorption band of the YAG:Nd^{3+}. Several

time constants were observed in the decay of the laser output from its short pulse value to the cw value; a 30-msec decay was associated with heating of the diode elements with respect to the heat sink and a 20-sec decay related to heating of the heat sink. A further 160-sec decay was connected with a rise in temperature of the laser rod heat sink, though in normal operation the thermoelectric coolers on this heat sink were set to hold the temperature constant.

One of the laser rods had flat parallel ends with one high reflectivity coating and one antireflection coating, so that it could be used with an external output mirror. Varying the radius of curvature of the output mirror caused a change in the TEM_{00} mode diameter; the larger the mode diameter the higher the threshold. This was attributed to the focusing of the GaAsP junction radiation in the YAG rod. The lowest threshold was found with another rod with a resonator configuration giving the smallest mode diameter. The authors proposed to achieve an efficiency increase in future work by using a wider diode array and a larger diameter laser rod with a larger TEM_{00} mode. They point out that the input power goes up linearly with array width while the output power goes up as the square.

At a drive current of 225 mA/diode, corresponding to input power of 30W, the optical output of the diode array was 0.90W, for an average power efficiency of about 3%. The 1.4 mW continuous laser output at 20°C corresponds to a total power efficiency of 0.005%. However, in millisecond pulse operation, the power efficiencies were higher; 4.9 mW for a 30W electrical input, and 15.7 mW for 44W input, approaching 0.04%. The authors expect that cw operation at close to the pulsed efficiency could be realized by more uniform heat sinking of the diodes in the array. Finally they point out that with the laser rod at 0°C, the pulsed output for an input of 44W was 55mW, giving an efficiency of 0.13%. Since it requires only 2W of power to the thermoelectric coolers to maintain the laser rod at 0°C, under cw conditions an overall efficiency of 0.12% could be anticipated for these conditions, once the heat-sinking of the diodes is made uniform.

These are, until now, the highest efficiencies reported or realistically predicted for diode-pumped laser operation near room temperature. The 77°K results of Allen and Scalise corresponded to 0.5%, and this might increase several times if the more efficient pumping cavity of the later experiments

were employed. It must be noted tha. the drive currents for the LEDs correspond to junction current densities of about 1700 A/cm^2. This is much larger than the usual values, on the order of tens of A/cm^2, for LEDs used in the visible region.

The TI-BTL work just reviewed has demonstrated some of the practical difficulties for diode-pumped lasers, as well as providing a background for the requirements on LED pumps for this application. Briefly, the LEDs must emit light within the pumping band of the solid state laser at a high e   iency. This limits the choice of material of the LED to those which can have their bandgap and hence emission wavelength "tuned" by varying the composition. For pumping YAG:Nd^{3+} with its pump band at 8100 Å, the present choices are the ternary alloys $GaAs_{1-x}P_x$, the material used by the TI-BTL workers, or $Ga_{1-x}Al_xAs$. These materials have received a great deal of attention for other LED applications and the technologies for preparing them and fabricating them into device structures are well-developed. The other materials which can be tailored to emit at 8100 Å, $In_{1-x}Ga_xP$ and $In_{1-x}Al_xP$, are much less advanced, but they are receiving attention for visible LED applications and should be considered as future candidates for laser pumping. Two recent reviews by Bergh and Dean and Nuese, et al. of the entire LED field have included discussions of the ternary systems, covering the theory of their operation and preparation methods, and giving extensive bibliographies. In the remainder of this report, we will draw on these review papers to summarize the design principles and preparation methods applicable to laser pumping diodes. We will also discuss recent work on $Ga_{1-x}Al_xAs$ high-efficiency LEDs suitable for laser pumping, and comment on the limited literature on degradation and reliability.

The tunability of bandgap in the ternary semiconductor alloys of interest for laser pumping, is a consequence of the change in electronic energy band structure with composition in these materials. In each case, the bands change from the direct gap structure characteristic of GaAs, for example, and at a particular crossover composition the lowest conduction-valence band separation becomes indirect. In a direct material, the lowest conduction band state is at the same point of the Brillouin zone as the highest state of the valence band, which leads to a high probability for radiative recombination of excess holes and electrons. In indirect materials, these states are at different locations in the Brillouin zone, and radiative recombination is generally much slower,

occurring only with the intervention of phonons or with the aid of impurity levels. Thus direct gap materials are much more efficient light emitters than the indirect ones, since competing nonradiative recombinations are less important, and this circumstance plays a central role in many LED applications, because the band gaps in the visible range are generally on the indirect side of the crossover composition. Fortunately for the $YAG:Nd^{3+}$ laser pumping application, the required band gaps are in the direct range of composition.

The mechanism of light emission in an LED is the radiative recombination of excess current carriers injected across a forward-biased p-n junction. Direct-gap semiconductors have a high internal quantum efficiency compared to indirect-gap materials for the reason just discussed. However, because of their higher radiative transition probabilities for light at or near the band-gap, direct-gap materials may absorb, within the LED itself, the light emitted at the junction. This is a problem for the laser-pumping diodes as well as for visible range LEDs, and has occasioned the development of special configurations to minimize the internal losses. The general principle of these schemes is to provide a path for the emergence of the light generated at the junctions through material of higher bandgap and hence lower absorption. The emergence of the generated light is also hindered by dielectric reflection effects at the interface between the diode and the external medium; ordinary reflection loss is minimized by anti-reflection coatings, while total internal reflection losses are avoided by using dome-like structures, so that the light is traveling nearly normal to the interface when it reaches the surface of the diode.

Electrical losses in the diode structure are kept low by maintaining a low diode series resistance by means of high doping levels and favorable geometrical design.

The details of the fabrication of the $GaAs_{1-x}P_x$ LEDs used in the TI-BTL laser pumping work were not given in the publications. However, $GaAs_{1-x}P_x$ diodes are usually fabricated by vapor-phase epitaxy. Suitable gaseous mixtures of arsenic and phosphorus (formed by the thermal decomposition of arsine and phosphine) with a gallium-chlorine compound (formed by passing HCl gas over molten gallium) react to form the ternary alloy as a deposit on a GaAs substrate. Dopants can be introduced in gaseous form at various times during the deposition or subsequently by diffusion. The process is very flexible, allowing precise control of the composition of the deposited layers through the flow rates of

the gaseous reactants. The basic process has been used commercially for several years, and is well adapted to volume production. It is usually necessary to grade the composition of the epitaxial deposit from pure GaAs to the desired composition of $GaAs_{1-x}P_x$ (by varying As/P ratio during the growth) in order to avoid the effects of lattice mismatch.

Liquid-phase epitaxy is the preferred growth method for $Ga_{1-x}Al_xAs$. The material is grown from a melt of gallium, gallium arsenide, and aluminum onto a substrate of gallium arsenide or sometimes gallium phosphide. Many refinements in the technique are available; some are discussed by Blum and Shih. The method has been particularly well developed in connection with the fabrication of heterostructure GaAs - $Al_xGa_{1-x}As$ laser diodes; a recent paper by Miller et al. describes a method to obtain high uniformity and reproducibility.

Reflecting the less advanced state of $Ga_{1-x}Al_xAs$ LED technology compared to that of $GaAs_{1-x}P_x$, there have been no reports of laser pumping with $Ga_{1-x}Al_xAs$ LEDs. However, several recent papers contain discussions of highly efficient laboratory diodes or of configurations which might be adapted for laser pumping.

Dierschke, Stone and Haisty have produced $Ga_{1-x}Al_xAs$ Zn-diffused LEDs emitting at 8150 Å. The power efficiency at maximum output at 25°C was 12%. The high efficiency is the result of a grading of the alloy composition so that light emitted at the junction emerges through material of higher bandgap than the junction itself. In their process, the ternary is grown on a GaAs substrate; because of the high distribution coefficient of aluminum in favor of the solid ternary, the melt is depleted of aluminum and the bandgap of the epitaxially deposited material decreases away from the substrate. The deposited layers are 0.03 to 0.06 cm thick and doped n-type by tellurium from the melt. The next step is the formation of a 0.011 cm p-n junction by zinc diffusion on the side away from the substrate. Then the GaAs substrate is removed and the units are formed into hemispherical domes. An anti-reflection coating of SiO is applied to the hemispherical surface and electrical contacts to the n and p regions on the plane surface of the hemisphere are made by means of metallization patterns on a silicon submount. The reported spectral bandwidths of the emitted light range from 250 to 670 Å, which indicates that in some cases light will fail to match the $YAG:Nd^{3+}$ pump band. The authors ascribe the wide bandwidths to location of the junction in regions with too high a composition gradient; since some units already have low bandwidth it may be expected that improved

control of the fabrication process will generally yield acceptable bandwidths.

Woodall et al have produced LED structures starting with a GaP substrate. The high bandgap of the substrate allows it to be included in the finished device without absorbing the junction light, and the layer of $Ga_{1-x}Al_xAs$ need not be so thick that it can survive separation from the substrate. In this work a four-melt system was employed for the liquid epitaxy; the substrate could be moved from melt to melt with or without losing the solid-liquid interface, and counterdoping of each melt during growth was possible. Phosphorus contamination arising from meltback of the GaP substrate in the first melt was greatly reduced by moving the substrate and the initial deposit to the next melt. Other melts allowed changes in the composition in addition to those caused by depletion of aluminum in the melt. In one structure, the composition was graded approximately linearly from the substrate to the junction. Each melt contained tellurium for n-type doping; the junction was formed by counterdoping the third melt with zinc during growth. A test device was formed into a mesa structure to allow contacts to both n and p regions on the same side. This diode emitted at 8500 Å with an external quantum efficiency of 1.2%. A similar structure with a roughly hemispherical dome formed in the GaP substrate had a quantum efficiency of 5.5%. An even more promising result was obtained with a structure in which the light was emitted in a region grown from a melt much less rich in aluminum than the other melts. This "minimum bandgap" structure is really a heterojunction device, since the junction is between a p-region of one composition and an n-region of another composition. A mesa diode of this type emitted at 8000 Å with 3% efficiency; presumably a dome configuration in the GaP substrate would increase this by something like the (5.5/1.2) ratio for the linearly graded device. Despite the observation of many metallurgical imperfections in these structures, they apparently do not affect the electroluminescent behavior of the active layers.

Burrus and Miller have described LEDs based on $Ga_{1-x}Al_xAs$ designed to couple efficiently to optical fibers. They deposited successively on an n-type GaAs substrate n-type $Ga_{1-x}Al_xAs$, an emitting layer of p-type $Ga_{1-y}Al_yAs$ (y less than x to make this the lowest bandgap region), p-type $Ga_{1-x}Al_xAs$, and p-type GaAs for contacting purposes. A 50 μm diameter contact dot was defined on the last GaAs layer, and the GaAs substrate was etched away above the dot so that it would not absorb the light emitted by the active layer. In this application, a clad optical fiber was attached by epoxy resin to the window

etched in the substrate. The light output near 8000 Å from a 30-cm length of fiber with an input current of 150 mA was as large as 1.7 mW. It may be interesting in the future to consider arrays of such units in which the emitted light is brought to a laser rod via optical fibers, eliminating the usual pumping cavity and to some extent allowing the LEDs to be geometrically and thermally decoupled from each other.

Like all semiconductor devices, LEDs are likely to suffer a change in characteristics, usually for the worse, during operation. Long operating life without excessive degradation of light output and efficiency is essential for the laser-pumping application of LEDs. The published empirical information on the degradation of units suitable for laser pumping is neither extensive nor conclusive at this time. $Ga_{1-x}Al_xAs$ emitters were lifetested by Dierschke, et al. at 25°C under a current density of 1500 A/cm^2; after 5000 hours the best ones had degraded less than 15%. The $Ga_{1-x}Al_xAs$ sources of Burrus and Miller were reported to have operating lives to half-output at 7500 A/cm^2 of at least several thousand hours. Double heterostructure laser diodes having a related structure have not yet achieved long operating lifetimes; Miller et al. report very substantial degradation after 25 hours of room temperature cw operation.

LEDs for visible display applications exhibit operating lives of many thousands of hours. Hartman et al. have given the most optimistic estimate of half-life for LEDs of 10^8-10^9 hours at room temperature. This is for GaP units specially passivated to prevent the introduction of impurities. Of course, visible LEDs are operated in the range of tens of A/cm^2, while the laser pumping diodes (at least those proposed so far) all require bias current densities above 1000 A/cm^2. Thus the operating conditions are much less favorable for long life for the laser pumps. There is some hope that degradation may be at least partially reversible. Burrus and Dawson, working with high current density GaAs light emitters found that applications of a periodic reverse bias with a duty cycle as low as 1%, slowed the degradation dramatically, and further, a previously degraded diode could be restored by heating at 100°-200°C, under zero or reverse bias for several hours to a few days. Possibly laser pumping is compatible with degradation-delaying bias schedules of this kind.

There is general agreement that the degradation of LEDs arises from bulk effects near the p-n junction. Schade, Nuese, and Gannon have provided direct

evidence that non-radiative defect centers do appear near the junction in $GaAs_{1-x}P_x$ diodes which have undergone degradation. Their measurement of thermally stimulated currents showed a greater number of centers in the more seriously degraded devices. Their results could not identify the defects, however, beyond assigning energy levels to them. The degradations were from 5 to 50% after 2000 hours of operation at 10 A/cm^2. Centers could have been formed by the Longini mechanism (the transport of charged interstitial impurities across a p-n junction into a region where they complex or precipitate) or by the Gold-Weisberg mechanism in which some of the energy liberated in nonradiative recombination generates vacancy-interstitial pairs. If the nonradiative recombination takes place at an impurity atom, the interstitial can be the impurity itself.

Bergh, working with GaP LEDs, showed that intentional introduction of copper accelerates degradation and careful elimination of contamination by copper and similar impurities greatly increased diode life. He concluded that the mechanisms of degradation, whatever they might be, were not inherent in the operation of the device. It remains an open question whether degradation can be sufficiently reduced in the ternary LEDs to make the laser pumping application really practical.

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APPENDIX

Gallium-Aluminum-Arsenic and
Gallium-Arsenic-Phosphorus Systems
Data Tables

M. NEUBERGER

These Data Tables provide the most reliable information available for the physical, crystallographic, mechanical, thermal, electronic, magnetic and optical properties of $Ga_xAl_{1-x}As$ and GaP_xAs_{1-x}. All data points are referenced. Where two or more documents present the same data values, all are cited. The bibliography which follows each of the data tables is arranged alphabetically by author; more than one document by the same author is distinguished by the letters A, B, C, etc.

Other III-V ternary systems for which data are available are included in "Handbook of Electronic Materials," Volume 7, III-V Semiconducting Compounds, Data Tables which is to be published by Plenum Press during 1972.

GALLIUM-ALUMINUM-ARSENIC SYSTEM

PROPERTY	SYMBOL	VALUE		UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		$Ga_xAl_{1-x}As$					
Density		x	g/cm^3				
		0	3.598		AlAs	300	Donnay
		34	4.29		closed tube, iodine vapor transport, single crystals deposited on high purity, (110) GaAs		Black & Ku
		42	4.40				
		95	5.24				
		100	5.307		GaAs		Bateman et al.
Color		10	orange		transmitted white light through epitaxial, CVD thin films on alumina ~ 4μ thick		Manasevit, Hindeman et al.
		20	red-orange				
		60	red				
		70	reddish black				
		80	black				
Symmetry		cubic					
Lattice Parameter	a_o		a_o (Å)				
		0	5.6605		AlAs		Ettenberg & Paff
		42	5.6581				Black & Ku
		100	5.65191		GaAs		Cooper
Thermal Expansion Coeff.		0	5.20	10^{-6}/°C	AlAs, linear from 20-1000°C, lattice match AlAs-GaAs at 800-1000°C complete	20°C	Ettenberg & Paff
		100	6.86		GaAs		Pierron et al.

Liquidus Isotherms

At. % of Liquidus				NOTES	REFERENCES
Ga	Al	As	T°C		
96.5	1.0	2.5	898	first solid for slow cooling of high gallium solutions	Panish & Sumski, Ilegems & Pearson (B)
94.0	1.0	5.0	952		
89.0	1.0	10.0	1037		
84.0	1.0	15.0	1082		
92.5	5.0	2.5	1002		
90.0	5.0	5.0	1067		
85.0	5.0	10.0	1140		
82.5	15.0	2.5	1074		

PROPERTY	SYMBOL	x	ϵ_∞	NOTES	TEMP. (°K)	REFERENCES
Dielectric Constant Optical	ϵ_∞	90-99.6	11.0	optical meas. n-type, polycrystalline	300	Sikharulidze et al.
		18	8.5	reflectivity meas. on single crystals	300	Ilegems & Pearson (A)

PROPERTY	SYMBOL	x	m_n	n(10^{18}cm^{-3})	NOTES	TEMP. (°K)	REFERENCES
Effective Mass Electron	m_n	90	0.071	1.32	reflectivity meas. on n-type, polycrystalline material, 30μ thick	300	Sikharulidze et al.
		94	0.074	1.60			
		96.5	0.070	1.63			
		99.6	0.064	1.80			

GALLIUM-ALUMINUM-ARSENIC SYSTEM

PROPERTY	SYMBOL	x	VALUE $E_{gd}(\Gamma_{15}-\Gamma_1)$	$E_{gi}(\Gamma_{15}-X_1)$	UNIT	NOTES	TEMP. (°K)	REFERENCES
Energy Gap	E_g							
Direct	E_{gd}	0	2.90	2.13	eV	AlAs		Kischio, Lorenz et al.
Indirect	E_{gi}							
		25	2.42	2.0		Schottky barrier photoresponse meas.	300	Casey & Panish
		34	2.30	1.95				
		48	2.12	1.86				
		55	2.0	1.85				
		68	1.82	-				
		85	1.6					
		100	1.4257			GaAs	300	Zvara

PROPERTY	x	E_{gd}	E_{gi}	E_1	$E_1+\Delta_1$	UNIT	NOTES	TEMP. (°K)	REFERENCES
Energy Band Structure									
	53		1.94	3.15	3.33	eV	molecular beam, vapor preparation, single crystal films, reflectivity meas.	300	Cho & Stokowsk
	57	1.97		3.06	3.27				
	75	1.81							
	80	-		2.97	3.16				
	83	1.67		2.96	3.14				
	87.5	-		2.93	3.14				
	90	-		2.92	3.13				

x	E_o	$E_c+\Delta_o$	E_1	$E_1+\Delta_1$	E_c'	$E_o'+\Delta_o'$	E_2	NOTES	TEMP. (°K)	REFERENCES
0	2.93	2.95						AlAs	300	Berolo & Woolley
25	2.49	2.54	3.5	3.7	4.7	4.75	4.85	electroreflectance meas. on LPE deposited, 1 mil thick layers on GaAs		
34	2.36	2.39	3.4	3.6	4.7	4.75	4.85			
48	2.16	2.19	3.25	3.5	4.7	4.7	4.9			
55	2.04	2.06	3.2	3.4	.		4.9			
68	1.80	1.83	-	-	-		4.9			
85	1.63	1.66	2.91	3.0	4.4	4.6	5.0			
100	1.42	1.45	2.9	3.0	4.4	4.6	5.0	GaAs		

PROPERTY	x	VALUE	NOTES	TEMP. (°K)	REFERENCES
Direct-Indirect Cross-over	64	1.92 eV	electroluminescence meas.	300	Dierschke et al.
	65	1.92	electroluminescence meas.	300	Berolo & Woolley

PROPERTY	SYMBOL	x	LO_1	LO_2	TO_1	TO_2	UNIT	NOTES	TEMP. (°K)	REFERENCES
Phonon Branch Spectra										
Longitudinal Optic	LO	0	49.60	-	44.89	-	meV	reflectivity meas. on single crystals	300	Ilegems & Pearson (A)
Transverse Optic	TO	18	49.60	31.98	45.25	31.74				
		47	47.87	33.48	44.89	31.98				
		55	47.61	34.46	44.63	32.24				
		59	47.10	35.46	43.65	32.37				
		62	46.75	35.71	44.15	32.49				
		68	46.36	35.96	44.15	32.99				
		79	44.89	36.02	43.65	32.37				
		92	44.63	36.08	44.15	33.11				
		100	.	36.21	-	32.24				

PROPERTY	SYMBOL	x	n	NOTES	TEMP. (°K)	REFERENCES
Refractive Index	η	18	2.9	reflectivity meas. on single crystals	300	Ilegems & Pearson (A)
		90	3.3	optical meas. on single crystals	300	Sikharulidze et al.

GALLIUM-ALUMINUM-ARSENIC SYSTEM

PROPERTY	SYMBOL	VALUE		UNIT			NOTES	TEMP. (°K)	REFERENCES
Electron Emission (Cold Cathode)		x	Wavelength (Å)	Emission Current Density (A/cm^2)	Efficiency (%)	Photo-sensitivity (μA/lm)			
		88	8700-8800	0.1	4.0	700-1000	LPE-deposited on doped GaAs, Cs_2O-covered	300	Schade et al. (A, B)
Use in a P.N. Junction Laser		x	Wavelength (Å)	TCD A/cm^2	Efficiency (%)	Power Output			
		75	8700	$5x10^3$	46-47	200 mW	double heterostructure junction laser, LPE, substrate: GaAs, n-type, Si-doped 1)n-, Sn-doped, GaAlAs, 10^{17} 2)n-,p-, doped GaAs, $1\text{-}8x10^{18}$ 3)p-, Ge-doped, GaAlAs, $5x10^{17}$ 4)p-, Ge-doped, GaAs, $5x10^{18}$ layers 0.5-1μ thick	300	Pinkas et al., Miller et al. (A, B)
			8460 9130	24 1100	50		large optical cavity, heterojunction laser diode, 400μ long, 2μ thick	300	Kressel et al.
				3600 2000		0.04 W 1.2 W	continuous wave oper. pulsed operation	300	
		60-80 94	8576 8540	1000 2500	30-40	20 mW	double heterostructure LPE injection laser, continuous operation; emits polarized light	311	Hayashi et al.
Electroluminescent Diodes		x	Wavelength (Å)	Current Density	η (%)	Power Output			
Quantum Efficiency	η		8150 6950	300 mA	14 4	60 mW	Zn-diffused diodes, LPE deposited on GaAs 10-15μ junction depth	300	Dierschke et al.
			6700		0.3 4.0		LPE deposited on GaAs n-, p-type layers, 2-5μ thick	300 77	Beneking et al.
			9300				Al^+ ion implantation of Zn-doped GaAs, 0.2μ thick	77	Lansperger & Marsh
			6700-7000				annealed 5 hr. at 900°C	77	
				TCD A/cm^2	Efficiency (%)	Luminance			
		62-67	6550	40	0.23	10^4 ft L	LPE deposited p-n junction, 5-7μ thick	300	Shih & Blum
						Power			
		70	7750-7940	7500		1.7 mW	double heterostructure, [illegible] thick, diode coupled to multimode optical fibers, 2000 hour operating life	300	Burrus & Miller
		10	5760 (strong)				Bi-doped single crystals, photoluminescence meas.	4.2	Bindemann et al.
Light Modulation				Phase Modulation	Bias Voltage				
		70	11530	160°	10 V	0.1 mW/1 MHz	1 mm length diode	300	Reinhart & Miller

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GALLIUM-ARSENIC-PHOSPHORUS SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		GaP_xAs_{1-x}				

Density

x	G*	G** (gr/cm³)	NOTES	TEMP. (°K)	REFERENCES
0	-	5.32	GaAs	293	*Jones et al.
13	5.20				**Abagyan et al.
38	4.89				
56	4.66				
60	4.62				
66	4.57				
72	4.51				
74	-	4.48			
78	-	4.42			
92	-	4.23-4.36			
100	4.14	4.16	GaP		

PROPERTY	VALUE	NOTES	REFERENCES
Color	yellow to dark cherry red	transparent, vapor transport preparation of elongated tablets	Abagyan et al.

Lattice Parameters a_o

x	Jones	Rubenstein	Cooper	Pierron et al.	Abagyan et al.	
	vapor epitaxy single cr.	single cr. I-vapor transport		I-vapor transport	gas-transport single cr.	
0	5.65332 (calc.)	5.6532	5.64191		5.6527	GaAs
10		5.6305				
13	5.618					
20		5.6103				
30		5.5890				
38	5.578					
40		5.5676				
41				5.5607		
50		5.5483		5.5565		
55					5.5624	
56	5.550					
60	5.538	5.5296				
66	5.510					
70		5.5094				
72	5.503					
74					5.501	
78					5.499	
80		5.4994				
90		5.4704				
92					5.473-5.482	
100	5.4505	5.4505		5.4495	5.4505	GaP

Melting Point M.P

x	M.P.	UNIT	NOTES	REFERENCES
0	1238	°C	GaAs	Richman
5	[illegible]			Osamura & Murakami, Antypas, Osamura et al.
15	1270			
45	1325			
60	1350			
65	1360			
73	1390			
90	1420			
100	1467		GaP	Richman

Thermal Expansion Coeff.

x	VALUE	UNIT	NOTES	REFERENCES
0	6.96	$10^{-6}/°K$	GaAs	Pierron et al.
41	5.41		from lattice constant meas.	
50	5.91			
100	5.81		GaP	

GALLIUM-ARSENIC-PHOSPHORUS SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP.(°K)	REFERENCES
Thermal	k	see table below		polycrystalline, Te-Se- and Si-doped $n_n = 2\text{-}4 \times 10^{16}$		Carlson et al.
Dielectric Constant Optical	ε_∞	see tables below		GaAs single crystals grown by closed tube, iodine vapor transport method; optical meas. in infrared		Clark & Holonyak
				GaP optical reflectivity meas. $n < 10^{16}$ cm^{-3}		Verleur & Barker
Mobility Electron	μ_n	see tables below		Gas transport, vapor phase, epitaxial, single crystals, $n_n = 1.5 \times 10^{15}$	300	Ogirima & Kurata
				epitaxial vapor deposition on (100) GaAs, not doped, $n_n = 5 \times 10^{15}\text{-}10^{16}$		Tietjen & Weisberg
				epitaxial, n-type, single crystal, closed tube, vapor deposition on (110) GaAs or GaP, iodine transport, Se, Te or Sn-doped	300	Ku
				epitaxial, n-type, single crystal, vapor deposition, Se and Te doped	300	Wolfe et al.
				single crystals		Yurova et al.

Thermal (Carlson et al.)

x	k (W/cm °K) 30°K	k (W/cm °K) 273°K
10	1	0.22
20	-	0.20
33-35	0.4	0.18
50	0.22	0.14

Dielectric Constant, Optical

GaAs (Clark & Holonyak)

x	ε_∞ 80°K	ε_∞ 300°K
0	10.4944	10.7479
6	10.3716	10.6314
12.5	10.2313	10.4601
25	10.0866	10.2909
35	9.9871	10.1632
41.7	9.8382	10.0331
62.5	9.5607	9.8203
100	8.8599	8.4980

GaP (Verleur & Barker)

x	ε_∞ 300°K
6	10.76
28	10.20
56	9.53
65	8.86
99	8.46

Mobility, Electron

Ogirima & Kurata

x	μ_n (cm^2/V sec)
38	3150

Tietjen & Weisberg

x	μ_n 77°K	μ_n 300°K
0-30	15000	5000
40		1300
70		500

Ku

x	$n = 1.5 \times 10^{17}$	$n = 6 \times 10^{17}$
0 GaAs	5000	4000
5	-	4000
10	5000	4000
15	4000	3000
25	2500	-
30	1500	800
50	250	-

Wolfe et al.

x	μ_n	n_n (10^{18} cm^{-3})
12	1580	1.0
20	900	-
25	700	1.0
34	400	-
45	100	0.2
50-60	25	1.0

Yurova et al.

x	μ_n (cm^2/V sec) 125°K	μ_n (cm^2/V sec) 300°K	Dopant	n_n (10^{19} cm^{-3})
70	160	85	Te	1.8
75	140	90	Te	2.1
80	80	60	Te+Zn	1.3
80	100	70	Te	5.0
80	150	90	Se	1.4
90	300	100	-	0.4

GALLIUM-ARSENIC-PHOSPHORUS SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP.(°K)	REFERENCES
Effective Mass Electron	m_n					

x	m_n	UNIT	TEMP.(°K)	REFERENCES
14	0.085	m_o	300	Hill, Craford et al.

Composition Coeff. $m_n = 0.072\ (1+x)$

x	$m_n (m_o)$	$n_n (10^{18} cm^{-3})$	NOTES	TEMP.(°K)	REFERENCES
20	0.12	2.7-4.1	optical reflectivity and Faraday rotation at 2-24μ on n-type material	300	Iglitsyn et al.
25	0.15	5.7			
30	0.18	2.5			
55	0.47	2.5			
72	0.47	2.5			

Energy Band Structure
Direct Gap, E_o
Spin-Orbit Splitting Δ_o

x	E_o	Δ_o	E_1	Δ_1	E_o'	E_2	UNIT	NOTES	TEMP.(°K)	REFERENCES
0	1.43	0.33	2.90	0.23	4.46	4.99	eV	GaAs	300	Thompson et al., Irzikevicius et al.
10	1.55	0.32	2.94	0.24	4.48	5.01		electroreflectivity meas., sealed tube, iodine transport, polycrystalline, n= 10^{17}; GaAs and GaP are single crystals		
20	1.67	0.28	3.01	0.22	4.52	5.05				
30	1.82	0.27	3.06	0.23	4.52	5.04				
40	1.90	0.25	3.14	0.23	4.58					
50	2.04	0.22	[illegible]	0.21	4.61	5.13				
60	2.16	0.19	3.27	0.19	4.63	5.17				
70	2.29	0.18	3.38		4.67	5.21				
80	2.44	0.16	3.41							
90	2.60	0.12	3.58		4.75	5.24				
100	2.75	0.09	3.66		4.75	5.28		GaP		
20	1.645	0.330	3.003	0.232	4.61			electroreflectance meas.	300	Rehn

x	$E_o+\Delta_o$	E_1	Δ_o	NOTES	TEMP.(°K)	REFERENCES
20	2.021	3.053			180	Rehn
28			0.275	optical meas. on single crystal, epitaxial films	300	Hodby, Belle et al.
43			0.242			
47			0.230			
70			0.190			
78			0.170			
87			0.250			

Indirect Gap E_i

x	E_i(eV) Ku	E_i(eV) Spitzer & Mead	NOTES	TEMP.(°K)	REFERENCES
25	1.85		optical meas. on I-vapor deposited, single crystal, epitaxial films	300	Ku
30	1.90				
40		1.65			
50	2.0				
55		1.92	photovoltaic and luminescence meas. on polycrystals		Spitzer & Mead
75	2.12				
80		2.06			
95		2.12			
100		2.19			
43-44	2.04 (cross over)		open tube, vapor deposited epitaxial film diodes on (100) GaAs, 5μ junction depth; electroluminescence meas.	77	Herzog et al.
45	1.94 (cross over)			300	

GALLIUM-ARSENIC-PHOSPHORUS SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP.(°K)	REFERENCES

Energy Band Structure

x	E_1 80°K	E_1 295°K	$E_1+\Delta_1$ 80°K	$E_1+\Delta_1$ 295°K	E_0' 80°K	E_0' 295°K	E_2 (eV) 80°K	E_2 (eV) 295°K	NOTES	REFERENCES
0 GaAs	3.0	2.9	3.22	3.13	4.45	4.42	5.1	5.05	sealed tube,	Woolley et al.,
10	3.09	2.95	3.24	3.18	4.49	4.5	5.15	-	iodine transport	Bergstresser
20	3.15	3.02	3.35	3.22	4.50	4.55	5.18	5.1	polycrystalline	et al.
30	3.20	3.10	3.38	3.30	4.60	4.5	5.20	5.25	or epitaxial	
40	3.24	3.18	3.39	3.32	4.55	4.70		-	layers, reflec-	
50	3.30	3.26	3.44	3.43	4.68	[illegible]	5.30	5.18	tivity meas.	
60	3.40	3.35	3.59	3.50	-		-	-		
70	3.48	3.42	-	-	4.77	-	5.32	-	reflectivity meas.	Williams &
80	-	3.50	-		-	-	-	-	on epitaxial layers	Jones
100 GaP	3.76	3.70	-		4.89	4.79	5.41	5.30		

Temperature coeff. dE_1/dT $\sim-6\times10^{-4}$ eV/°K — 80-295 — Woolley et al.

Energy Gap E_g

x	77°K	295°K	dE_g/dT $(10^{-4}$ eV/°K)	NOTES	REFERENCES
18	1.79	1.69	3.2	optical meas. on	Subashiev &
29	1.85	1.77	3.54	epitaxial, 2μ layers,	Chalikyan
41	2.00	1.90	3.64	$n\sim10^{17}$	
52	2.18	2.10	3.54		
56.7	2.00	2.30	3.64		
86	2.50	2.46	3.64		

Composition coeff. $E_g = 1.51 + 1.16x + 0.2x^2$ — 77 — Subashiev & Chalikyan

$= 1.43 + 1.15x + 0.2x^2$ — 295

Temperature coeff. dE_g/dT $\sim-5\times10^{-4}$ eV/°K — 77-295 — Subashiev & Chalikyan

Pressure coeff. dE_g/dP

x	Value	NOTES	TEMP.(°K)	REFERENCES
49	1.3×10^{-6}/kg cm^{-2}	polycrystalline, Te-doped P to 10 kbars; electrical meas.	77	Likhter & Pel

Energy levels

	Symbol	x	Dopant	E_d (eV)	E_a	dE_d/dP (eV/kbar)	NOTES	TEMP.(°K)	REFERENCES
Donor	E_d								
Acceptor	E_a	37.5	Te	0.03		10.5×10^{-3}	electrical meas.	55-400	Craford et al.
		30	S	0.04					
		45	S	0.21		10.8×10^{-3}			
		35	S	0.0[illegible]		10.0×10^{-3}		77	
		50	Fe		0.61		thermally stimulated conductivity, 2×10^{15}	90-350	Schade

Phonon Branch Spectra

Transverse Optic TO

x	TO	UNIT	NOTES	TEMP.(°K)	REFERENCES
6	44.6	meV	reflectivity meas. $n\sim10^{16}$	300	Verleur & Barker
28	46.5				
56	47.8				
85	49.8				
100	50.2				

GaP

x	L TO	L LO	L LA	L TA	X TO	X LO	X LA	X TA	NOTES	REFERENCES
5.4	43.5			10.4					open tube 300	Chen et al.
17.7	44.0		32.8	10.4					vapor trans-	
35	44.1		33.0	10.4					port epitaxial	
48	44.4		33.4	10.2					films on (111)	
67.5	45.0		33.9	9.55					GaAs	
85	45.7	39.8	34.5	8.60	44.4	37.2	33.8	14.9		
100	46.5	40.8	34.7	8.49	44.7	38.3	32.8	14.5		

GALLIUM-ARSENIC-PHOSPHORUS SYSTEM

PROPERTY	SYMBOL	VALUE		UNIT	NOTES	TEMP. (°K)	REFERENCES
Magnetic Susceptibility	χ_{mol}	x	$-\chi$ mol				
		0	32	10^{-6} cgs	GaAs	300	Andrianov et al.
		30	30		single crystal, $n \sim 10^{17}$		
		45	28		Faraday rotation meas.		
		71	28		at 77-300°K		
		75	27				
		100	27		GaP		

Refractive Index

x	87°K Wavelength 2.07μ	1.03μ	0.78μ	0.62μ	300°K Wavelength 2.07μ	1.03μ	0.78μ	0.62μ	NOTES	REFERENCES
0	3.27	3.43			3.33	3.47			closed tube,	Clark &
6	3.26	3.4			3.30	3.45			halogen vapor	Holonyak
12.5	3.22	3.35			3.26	3.41			transport,	
25	3.21	3.31	3.45		3.24	3.35	3.52		polycrystals,	
35	3.18	3.28	3.40		3.22	3.33	3.47		Se- or Te-doped	
41.7	3.16	3.25	3.37		3.19	3.29	3.43		$n \sim 10^{18}$	
62.5	3.10	3.20	3.30	3.47	3.14	3.23	3.35	3.52		
100	-	3.07	3.15	3.28	-	3.11	3.20	3.33		

Photoemission Quantum Yield Y
*(electrons/quantum)

x	Y*	Wavelength (Å)	NOTES	TEMP. (°K)	REFERENCES
25	38 mA/W	4000	cesium activated p-type photocathode	300	Simon et al.
0-17	0.21*	6000	cesium coated, Zn-doped,		Garbe
30	0.10	6000	closed tube, iodine		
	0.25	5000	vapor transport crystals		
70	0.01	5000			
	0.20	4100			
100	0.19	4100			
	0 0	5000			

Diode Properties
Brightness B
Quantum Efficiency η
Current Density CD

x	B(fL)	Wavelength (Å)	η (%)	CD (A/cm²)	NOTES	TEMP. (°K)	REFERENCES
40 29	720	6520	0.2 0.6	4.4 4.4	Zn-diffused, vapor grown, epitaxial films, $n \sim 10^{16}-10^{17}$	300	Herzog et al.
38		9500	0.2	0.08	2×10^{16}	300	Ogirima & Kurata
40	1000	6450		10	vapor grown, $10^{17}-10^{18}$	300	Burmeister et al.
40	max.	6530	0.05	10	$n \sim 10^{17}$, selenium doped epitaxial layers, cathodoluminescence meas. 1.2-1.5μ junction depth	300	Heath & Stewart
76	200	5850	0.002	16	Zn-diffused, vapor grown, epitaxial diode, 5.5×10^{16}, 0.3-0.4 mm² area	296	Epstein & Huebner
45	400-600 (at 10 A/cm²)	6640	3.5 0.2	20	Zn-N doped Zn-doped, vapor phase, epitaxial EL diodes	300	Groves et al.
34-37			2.75 0.21		EL diodes $n \sim 4 \times 10^{17}$	78 300	Maruska & Pankove
28 42	>300 8500	6800 6600	0.035 0.4	10	vapor grown EL diodes	300	Nuese et al. (A, B)

GALLIUM-ARSENIC-PHOSPHORUS SYSTEM

PROPERTY	SYMBOL	VALUE			UNIT	NOTES	TEMP.(°K)	REFERENCES
		x	Å	η (%)	TCD (A/cm^2)			
Laser Properties								
Threshold Current Density	TCD	20.0	7250		9×10^2	vapor deposited,	78	Tietjen et al.
		40.5	6750		9×10^5	epitaxial films	300	
		14	8100	25	9×10^2	25W power output	300	
		10	7850		1.[illegible]-1.3×10^3	Te-doped, vapor grown single crystal, epitaxial films 10-16μ junction depth	77	Eliseev et al.
		15	7585					
		20	7400					
		30	6890					
		35	6640					
		45	6390					
		30	6750			vapor grown, thin platelets	77	Johnson & Holonyak
Memory Effect, (Lifetime)		3 millisec. at 6500 Å					77	Eliseev & Ismailov

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